MONOPLOTTING – A SEMI-AUTOMATED APPROACH FOR 3D RECONSTRUCTION FROM SINGLE SATELLITE IMAGE

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ABSTRACT:

In this paper, we present a semi-automated approach to high quality three-dimensional (3D) objects reconstruction from single high-resolution satellite image using monoplotting technique. The method requires high accuracy of satellite sensor model, such as Rational Polynomial Coefficients (RPC), and high resolution of Digital Elevation Models (DEM) to achieve the high precision geometry of the 3D reconstructed object. The RPC is used to determine the ray of the satellite to the object, while the azimuth and elevation angles of the Sun is used to determine the shadow of the object on the ground. The vertices of the polygon, which are manually extracted from the top surface of an object, are used for the prediction of the base and shadow positions on the 2D satellite image based on the height of the object. Once the predicted base and shadow positions match their positions in the image by observation, the height of the object is determined. As a consequence, the 3D object is reconstructed simultaneously. We have developed a full suite of the software for realtime extracting, editing, reconstructing and visualising of the 3D objects from single IKONOS image.

1. INTRODUCTION

The high accuracy Rational Polynomial Coefficients (RPC) sensor models and stereoscopic images of IKONOS satellite allow us to extract 3D spatial information and build digital city models with high geometric accuracy. However, the demand for reconstructing the city model from single satellite image is increasing due to the data availability, weather condition, timing and cost. Monoplotting, a photogrammetric technique, is able to extract 3D spatial information from single image with the availability of high resolution digital elevation models (DEM).

For the flat top of a 3D object, its position in a 2D image can be derived with the RPC, which defines the ray from satellite to the object. The ray intersects the ground and the height at this intersection point is given by the DEM. The object can be re-positioned to its 3D coordinate along the ray direction with its base landed on the ground. Once the height of the object is measured, its 3D geometric position is unique.

There are a few methods to derive the height of the building: (1) from satellite azimuth and elevation angles; (2) from sun azimuth and elevation angles; and (3) from RPC. Satellite angles show the building top relative to its base, while the sun angles show the shadow of the building top relative to its base. By measuring the distance from top to base or from top to shadow in image space (pixels), the height of the building can be obtained in ground space (meters). However, the accuracy of the obtained height depends on the accuracy, size or the difference of the satellite and the Sun angles, and these values given in the image auxiliary data are not always very accurate for the whole strip of scene. RPC on the other hand, generates the building height with higher accuracy by measuring from top to base, but loses its accuracy when the base is not clearly shown in the image.

To achieve higher accuracy for the height extraction, we design an interactive platform for the user by combining the above methods. Instead of the conventional ways of measuring the length of an object, we use the reverse method by changing the height of an object to predict its locations of base and shadow in the image. With the polygon of the flat top of an vertical object drawn, the line from each vertex of the polygon to its base, and line from vertex to its shadow are also drawn according to the height of the object. Changing the height of the object will change the position of the polygon in 3D (map coordinates), as well as change the position and length of the lines in 2D (image space). Once the lines touch the ground base or the shadow edge by observation, the height is set, and the position is fixed.

This paper presents a semi-automated method for height measurement and 3D object reconstruction from single image by combining the above methods using the building top, base and shadow information. We also design an interactive software system for realtime 3D reconstruction, multi-dimensional visualization based on our previous development of a 3-D visualization system (Huang et al., 2006) to provide a complete package.

The software package has been implemented on a standard PC running the windows operating system. A user-friendly graphical user interface complete with drawing and editing tools and a 3-D visualization component is introduced. The geometric accuracy of the 3D objects reconstructed from single image is compared to those generated from stereo images due to the lack of 3D ground truth data. Fortunately, the 3D information from stereo images is achieved quite reliably.
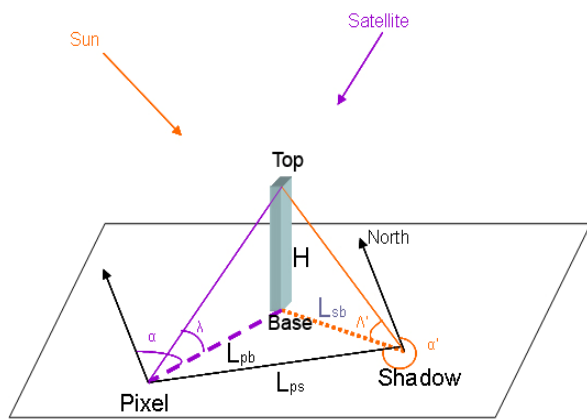
Figure1. Geometry of the 3D building with the position of the sun and the satellite

Figure2. 2D satellite image of a building with the base and shadow clearly located. *p* is the top, *b* is its base and *s* is its shadow.

2. STEREO VS MONO IMAGE FOR HEIGHT EXTRACTION

In a typical imaging system, the 3D real world object after passing through the camera/sensor is project onto a 2D image. The mathematical model that links the 3D object coordinates to the 2D image coordinates is known as the camera model.

$$(l, s) = CameraModel(\phi, \lambda, h)$$

Where (ϕ, λ, h) is the 3D object coordinates and (l, s) is the 2D image coordinates. A popular replacement camera model that is used by IKONOS and other satellite systems is the Rational Polynomial Coefficients (RPC):

$$(l, s) = RPC(\phi, \lambda, h)$$

Whether rigorous Camera Model or RPC, one can see that to invert the process, i.e. to compute 3D object from 2D image coordinates with one image, one has three unknowns (ϕ, λ, h) and two observations (l, s) which cannot be solve uniquely. The usual solution is to use another image that covers the same object, i.e. use of stereo imagery.

If we know the height, e.g. from known DEM, the latitude and longitude of the object which is on the ground (in our case, the base of the building) can be determined.

With the simple geometry as seen in Figure 1, we can deduce that the height of a building (relative height coordinates) can be computed without knowledge of the DEM, provided the building is vertical, i.e. same latitude and longitude coordinates. The DEM is required to determine the latitude and longitude coordinates of the base (which is same as the latitude and longitude of the top of the vertically standing object). The last fact is very important as it allow us to measure the building location and height with any coarse DEM and to improve the accuracy of the location and height (which is unchanged) when more accurate DEM is available without the

need to remeasure all the buildings. A function of the software for this task has been implemented in the package as well.

3. RPC SENSOR MODEL REFINEMENT

For high accuracy determination of object coordinates from image coordinates or vice versa, there may be a need to improve the camera model with ground control points (GCPs). In traditional photogrammetry, the GCPs are used to refine physical orientation parameters such as the rotation angles and/or translation shift. For RPC, the rotation and translation parameters are all absorbed into the cubic polynomials. Luckily there are other indirect techniques for refinement of the RPC camera model.

One way is to finetune the normalized sample and line parameters of the RPC in image coordinates (Fraser et al., 2003, Grodecki et al., 2003) with an affine transformation:

$$\begin{aligned} s' &= a_0 + a_1 \cdot s + a_2 \cdot l \\ l' &= b_0 + b_1 \cdot s + b_2 \cdot l \end{aligned} \tag{1}$$

where

s' and l' are sample and line coordinates of the GCP calculated from RPC;

s and l are the sample and line coordinates of GCP observed in the satellite image;

a_0, a_1, a_2, b_0, b_1, b_2 are the adjustable coefficients.

This is akin to early days of aerotriangulation strip adjustment with polynomials.

We have developed a method to refine RPC in space domain by finetuning the object space latitude, longitude and height parameters of the RPC with the following set of equations:

$$\phi' = a_0 + (1 + a_1) \cdot \phi + a_2 \cdot \lambda$$
$$\lambda' = b_0 + b_1 \cdot \phi + (1 + b_2) \cdot \lambda$$
$$h' = c_0 + c_1 \cdot \phi + c_2 \cdot \lambda + h \quad (2)$$
$$(l, s) = RPC(\phi', \lambda', h')$$

where

s and l are sample and line coordinates of the GCP in the image ;

ϕ, λ and h are the longitude, latitude and height of GCP, respectively;

ϕ', λ' and h' are the refined longitude, latitude and height of GCP, respectively, consistent with the RPC transformation;

a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1 and c_2 are the adjustable coefficients.

Under appropriate conditions, some of the coefficients may be held fixed. The refined RPC can achieve an accuracy of less than 1m. A new set of refined RPC can be obtained from the coefficients.

4. HEIGHT OF AN OBJECT

To obtain the height of a building from a single IKONOS image, most of the methods measure the distance from the top to the base of an object (Willneff, et al., 2005), or from the top to the shadow (Irvin et al., 1989; Lin et al., 1998; Bouguet et al., 1999; Hui et al., 2000; Hinz et al., 2001).

Figure 1 shows the geometry of the systems of rays, from the Sun and the satellite position when the 3D building is imaged. Figure 2 shows an example of 2D satellite image of a building with its top, base and shadow clearly located. From the geometry, we can see that the top point of the building in 3D geometry will be shown as $p(l, s)$ in a 2D satellite image, while its base will be located in $b(l_b, s_b)$, and its shadow will be formed in point $s(l_s, s_s)$. By measuring the length L_{pb} from p to b, or the length L_{ps} from p to s in the 2D image, the height h of the building can be easily derived with (3), or with (4) to (6):

$$h = \tan \lambda \cdot L_{pb} \quad (3)$$

$$h = \tan \lambda' \cdot L_{sb} \quad (4)$$

$$L_{ps}^2 = L_{pb}^2 + L_{sb}^2 - 2 \cdot L_{pb} \cdot L_{sb} \cdot \cos(\alpha - \alpha') \quad (5)$$

$$h = \frac{L_{ps}}{\sqrt{\dfrac{1}{\tan^2 \lambda'} + \dfrac{1}{\tan^2 \lambda} - \dfrac{2 \cdot \cos(\alpha - \alpha')}{\tan \lambda' \cdot \tan \lambda}}} \quad (6)$$

where
α = azimuth angle of the satellite
λ = elevation angle of the satellite
α' = azimuth angle of the Sun
λ' = elevation angle of the Sun

The azimuth and elevation angles of the satellites and the sun are available from the image metadata file. The accuracy of the height derived from the distance between top and base, is directly proportional to $\tan \lambda$, while for method of measuring distance of shadow, it is relative to both λ and λ', and the difference between azimuth angles of the sun and satellite. It is obvious that the smaller the elevation angle of the satellite or the longer the shadow formed in the image, the more accurate the height obtained. For 1m resolution image, L_{pb} and L_{ps} can be measured within 1m accuracy if the base and shadow can be shown clearly in the image.

While the sun angles are consistent during the image acquisition duration of a few seconds, the satellite angles actually vary over the imaging period, thus the set of angles given in the IKONOS metadata file is usually not sufficient to derive the heights accurately for all buildings over the scene.

We develop a semi-automated method in a reverse way using the top, base and shadow information. Instead of locating the base or shadow in the 2D image, and measuring the distance from top to base or shadow edge, the new approach reduces two-dimensional problem into one dimension. The new approach is to change the height of the object, and predict the locations of the base using RPC and the shadow edge using both RPC and the angles of the azimuth and elevation of the sun.

The sensor model RPC provides accurate 3D map coordinates $(x, y, h + h_b)$ to 2D image point $p(l, s)$ (7) through the entire scene. The base point $p_b(l_b, s_b)$ has the same map coordinates as the top point $p(l, s)$ but with different height, its 3D coordinates are (x, y, h_b) (8). The shadow point $p_s(l_s, s_s)$ can be expressed in terms of l, s, h and angles of the sun (9-10).

$$(x, y, h + h_b) \xrightarrow{\ RPC\ } (l, s) \quad (7)$$

$$(x, y, h_b) \xrightarrow{\ RPC\ } (l_b, s_b) \quad (8)$$

$$l_s = l - \int_0^h \frac{\partial l}{\partial h} \cdot dh - h \cdot \frac{\cos \alpha'}{\tan \lambda'} \quad (9)$$
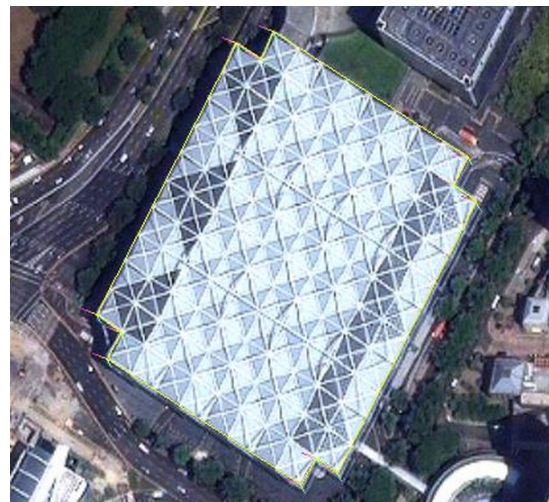

Figure3. The height of the building derived from shadow is 31m.

$$s_s = s - \int_0^h \frac{\partial s}{\partial h} \cdot dh - h \cdot \frac{\sin \alpha'}{\tan \lambda'} \qquad (10)$$

$$(x, y) \xrightarrow{\quad DEM \quad} h_b \qquad (11)$$

The terms $\partial l / \partial h$ and $\partial s / \partial h$ can be derived from RPC (7). They can be considered as local satellite angles. We assume that the base of a building lies on the ground with height h_b (11) of DEM (SRTM).

The method using RPC to determine the base or shadow of the top from changing the height is obviously more accurate than the conventional methods which locate the base and shadow first, measure the distance, then derive the height of an object. The new method reduces adjustable variable to height only so as to improve the accuracy. In our work to follow, we will concentrate on using the new approach to extract the building heights. The conventional methods can be use if RPC is not available.

In a satellite image, it is common that the base of a building is obscure by the surrounding structures, or the shadow may lie on top of the nearby building or be occluded by the building itself or nearby buildings. Depending on the situation, the new approach provides users the choices simultaneously. Figure 3 shows an example of the new approach to obtain the correct height of the building when only shadow can be observed clearly.

5. SYSTEM DESIGN

The system is based on our previous in-house development for a 3D city model visualization system (Huang et al., 2006). Figure 4 shows the system design. Briefly it implements two types of tasks, one is to visualize the existing 3D models in realtime, second is to reconstruct the new models simultaneously. In order to render large amount (Gigabytes) of data of satellite image, thousands of 3D models, a system has been developed to support:

i. an efficient database for managing DEM, satellite level 2A image and ortho-rectified ground image;

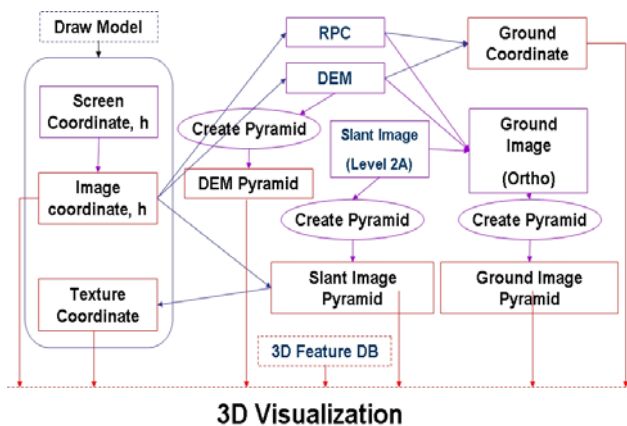ii. a level of detail (LOD) method for reducing computational load;

iii. a custom designed 2-D virtual memory management system for the optimal performance balance between image rendering speed and hardware requirements;

iv. a user-friendly interface for collecting outlines of new models.

The visualization platform provides user 2D and 3D view of the objects simultaneously.

5.1 Hierarchical Level of Detail

In the system, the ortho-rectified image of the original IKONOS level 2 image is used as ground texture in the 3D viewer. It is generated when the level 2 image is ortho-rectified with the refined RPC and the same DEM. The level of detail (LOD) to DEM for terrain, to ortho-rectified image for ground, and to level 2 image for 3D feature is applied. The automated LOD selection will be performed by the engine of the platform according to the distance between the camera's view point and the target.

5.2 Software User Interface for 3D Extraction

The software user interface is shown in fig. 5. The overview of the image coverage is shown on the upper-left corner of the window, the 2D satellite image is shown on the right of the window, while the 3D models, imported and newly generated, are shown on the lower-left corner of window, the orthorectified image and DEM are shown on the ground. Users are free to switch between 2D and 3D view as full screen. The software provides user a set of tools for various uses. The drawing tools are used for digitizing the building top in 2D view. The guidelines from the top to base, and from the top to shadow are drawn automatically according to the RPC, sun geometry and user candidate building height. The candidate building height can be either input from the keyboard, or varied by rotating the mouse central wheel.

An example of the software application is shown in fig. 6 and fig. 7. Figure 6b and 7b are part of the same satellite image. The outline of a building top has been drawn in yellow by the user. The guidelines in cyan are from the building top to base, and

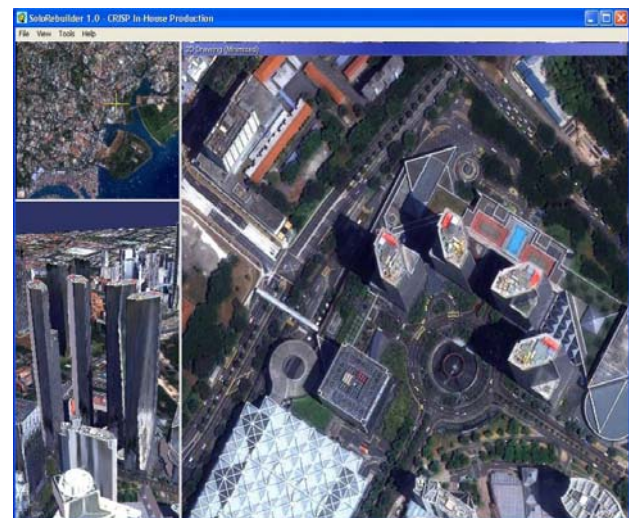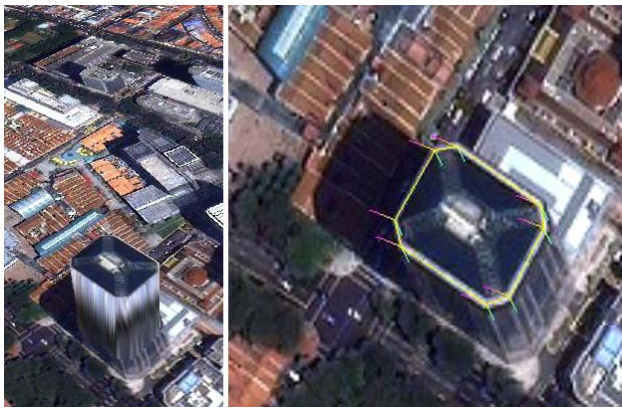Figure4. System Design

Figure5. Software user interface
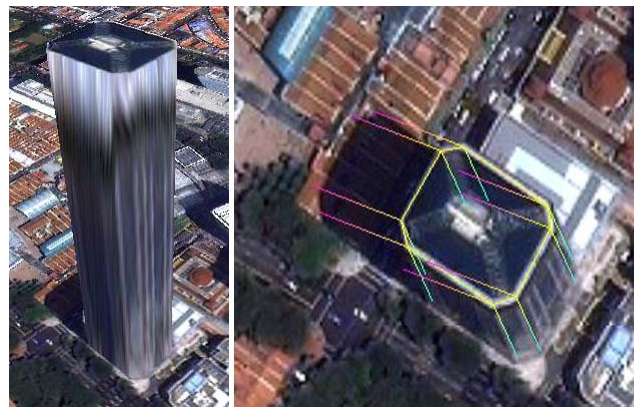
(a)   (b)

Figure6. (b)In IKONOS 1m resolution image, an outline of a building is drawn in yellow, the lines from top to base in cyan, top to shadow in magenta, length of the lines is corresponding to height of 36m;

(a) the 3D reconstructed building when height is 36m.

(a)   (b)

Figure7. (b)Similar to fig. 6b; lines touch the base or shadow when height is 125m;

(a) the 3D reconstructed building when height is 125m. Texture of the building matches the ground.

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guidelines in magenta are from the building top to shadow.

For example, when the building height is set to 36m as in fig. 6, the reconstructed 3D building is shown in fig. 6a. It is obvious that the guidelines do not reach the base or shadow edge (fig. 6b), the 3D object is also out of position (fig. 6a), and part of the texture for the side of the building is still on the ground when the height is not accurate. As the user changes the height interactively, the length of the guidelines change accordingly, and the 3D object moves its position. Figure 7 shows the guidelines touch the base or shadow edge, the object moves to its exact location, and its texture matches the ground texture perfectly when the height is set to 125m.

In the software, the guidelines from top to base, and top to shadow are drawn automatically with the change of building height. It is easy for the user to stop moving the mouse wheel as soon as the guidelines touch ground or touch shadow edge. The building height is thus set and 3D geometry is derived. The advantage of showing all the outlines to their base and shadow is that it enables the user to find the height even when there is only one base or shadow point seen clearly, and it also enables the user to choose the best match when more points are available.

The software provides the reconstructed 3D models an instant view. When the outline of an object is drawn, the triangulation of the polygon will be performed to provide a set of triangles, vertices and texture coordinates. The software will re-calculate the vertices of geometric position and texture coordinates whenever the height of an object is changing. The facades of the object facing the satellite are also determined, therefore, they will dress on the texture from satellite image, while those away from satellite will be in gray. As a consequence, the 3D object, fully textured and rendered, is shown in the 3D viewer. This enables the user to have a visual inspection of the building feature in almost realistic 3D. The usual functionalities, such as zooming in and out, rotating and viewing in different angles, are also provided for the 3D views.

5.3 Data Import, Export and Updating

An important function provided is that existing 3D city models can be imported to this system for updating, and the new 3D models generated by the system can be merged and incorporated for later exportation to other systems. This system is currently able to import and export 3D models to ASCII format, which is compatible to Leica Photogrammetric Suite (LPS) and Socet Set ASCII format, and Shapefile format, which is a popular GIS format that most commercial software supports.

Meanwhile, we have designed the internal format to memorize the coordinates of the objects in the satellite image as well. When the higher resolution of DEM is available, more GCPs are provided, or higher accuracy of RPC is provided, the software is able to update 3D geometry of the objects automatically.

6. TEST SITE AND ACCURACY ASSESSMENT

As mentioned above, the accuracy depends on the satellite acquisition and sun geometry. The larger the satellite elevation angle, the poorer the accuracy of 3D geometry; the larger the sun elevation angle, the poorer the accuracy of 3D geometry. For measurement of building heights, it is preferable to choose the image with smaller elevation angles. However, for the image ortho-rectification, which will be overlaid on top of DEM as ground texture, it is preferable to have an image with larger elevation angles.

Figure 1. IKONOS image of test site with height (m) labelled in yellow © CRISP

A simple accuracy assessment has been performed by comparing the building height derived from single IKONOS image using the software with that derived from a stereo pair of aerial photograph 1:10000. The azimuth and elevation angle of the satellite and the sun of the image for monoplotting are listed in table 1. The IKONOS image of the test site is shown in fig. 8. The height of the buildings derived from stereo aerial photos is labelled in yellow. DEM of 90m/pixel resolution is applied. The 3D geometry of the objects extracted from the satellite image with the software is compared to that generated with the stereo pair of aerial photos. 51 samples have been compared, with the largest disparity in height of 10m and smallest of 0.2m. The rms for the height of the objects is about 2m, while the accuracy in map coordinates is also about 2m.

TABLE I. The azimuth and elevation angles of the satellite and the sun of the IKONOS image

	α	λ	α'	λ'
Image	192.9323	72.96125	125.6500	60.2592

7. CONCLUSION

The new method for monoplotting is described. It reduces the measurement from 2 dimensions to 1 dimension, thus increase the accuracy in height measurement. It combines methods using both the base and shadow information to suit different situations. Therefore, whenever one base point or shadow edge of the vertex of the building top is clearly located in the image, the 3D flat building can always be reconstructed.

The high geometric accuracy of the 3D models can be achieved on certain conditions: i) high accuracy of RPC; ii) high resolution of DEM; iii) small elevation angle of the sun to have long shadow; iv) small elevation angle of the satellite to have long length of top to base; and v) the coarse density of the objects to avoid overlay the shadow on top of nearby objects.

The method has been implemented in a standard PC system. A software suite for realtime 3D reconstruction and visualization has been established.

There are several areas for future work, such as to extend 3D modeling for some slope roofs or non-flat roofs. We hope accomplish these in the next version of the software suite.

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